Appendix C The Phenomenology of Natural Hazards Covered

C.1 Introduction

This chapter provides a general qualitative description of the natural hazards described in this document. The function of this section is two-fold.

(1) An understanding of the natural hazards phenomena under consideration is critical to modeling them and hence developing risk reduction measures. (Chapter 3 contains guidelines for preliminary quantitative modeling of natural hazards considered in this document.)

(2) Water utility decision-makers and their technical staff and/or consultants can rank order the natural hazards in order of severity to a system in order to scope which natural hazards are of special interest to the water utility given the specific issues to be addressed.

This chapter provides initial screening only on the basis of small-scale maps and qualitative considerations. Additional considerations to be borne in mind include the specific issues that the water utility system is considering (e.g., the determination of the design parameters to be used for a water storage reservoir) and larger-scale maps that exist, for instance, in state geological surveys or elsewhere.

Section C.2 covers the phenomenology of ground movement hazards: general considerations (C.2.1), gravity landslide (C.2.2), expansive soil (C.2.3), soil collapse (C.2.4), and frost heave (C.2.5).

Section C.3 covers the phenomenology of flood hazards: general considerations (C.3.1), riverine flood and scour (C.3.2), and headwater flood and scour (C.3.3).

Section C.4 covers the phenomenology of windstorm hazards: general considerations (C.4.1), general severe wind (C.4.2), tornado (C.4.3), hurricane—general considerations (C.4.4), hurricane-tornado (C.4.5), hurricane-cyclone wind (C.4.6), hurricane-storm surge and scour (C.4.7), hurricane-headwater flood and scour (C.4.8), and hurricane-riverine flood and scour (C.4.9).

Section C.5 covers the phenomenology of earthquake hazards: general considerations (C.5.1), fault rupture (C.5.2), shaking (C.5.3), landslide (C.5.4), lurching (C.5.5), liquefaction (C.5.6), tsunami (C.5.7), seiche (C.5.8), and fire following (C.5.9).

C.2 The Phenomenology of Ground Movement Hazards

C.2.1 General Considerations

Ground movement hazards are defined as such because external forces or meteorological conditions affect the movement or failure of the earth materials. In the case of gravity landslide, the external triggering force may be gravity coupled with moisture changes. This is differentiated from earthquake-generated landslide which involves gravity, but the landsliding action is initiated or triggered by the earthquake shaking action. Soil collapse is also initiated by gravity.

Expansive soil hazards are initiated by changes in moisture conditions (usually dessication) within certain kinds of soils. They expand differentially with the addition of water and contact or shrink differentially with desiccation.

Frost heave results in differential movement of the surficial soils that have water accumulated in the interstices between soil grains. When water freezes, the resultant ice gains about 10 percent in volume, thus causing differential movement.

C.2.2 Gravity Landslide

Landslides are a form of earth movement down slope under gravity loads. The speed of movement can be either slow or fast. Landslides can vary from less than one acre (4047 sq meters) to several square miles (2.59 sq km/mile) in extent and include a variety of types. Smaller landslides are predominantly rotational slumps. The larger landslides are usually earth-flows.

Debris flows are moving, fluid masses of rock, soil and debris. They are active geologic processes in the Rock Mountains, and historic debris flows have affected several communities. Debris flows usually start as shallow landslides on colluvial slopes which are steeper than about 50% as a result of intense thunderstorm precipitation or rapid infiltration of snow pack melt. The flows thin out and spread laterally on alluvial fans where hillside channels may join a main valley. The flows have the capacity of transporting very large boulders. When confined in steep, hillside channels flow depth can reach 20 feet (6.09 m.) or more. Flow depths on the fans are typically in the range of 2 to 15 feet (0.61m. to 4.57m.) with the greater depths near the fan heads. Flow velocities can vary widely depending on depth of flow, gradient and ratio of water to solids. Velocities in the range of 1 to 30 mph (1.609 km/hr to 48.3km/hr) are typical of debris flows.

Rock fall is the precipitous movement of newly detached rock blocks from a cliff or other very steep slopes. In the Rocky Mountains, rock fall is common on many highway cuts in jointed rock. Rock fall also occurs along cliffs which border many mountain valleys. In a few areas rock fall blocks have reached downslope developments and transportation corridors. Rock fall can occur anytime of the year, but it is most frequent in the spring when there is repeated freezing and thawing of water in the rock joints. After dislodging from the outcrop, rock fall blocks travel rapidly downslope generally in a relatively straight line by a series of leaps and bounces. Individual rock fall blocks can vary from less than one foot to (0.3m) tens of feet (3m) in size depending on the joint spacing at the outcrops.

Selected Sources. There are a number of federal, state, and local agencies mapping gravity landslides. Godt, 1997, provides one small-scale landslide map for the co-terminous United States. An earlier small-scale map is provided by Krohn and Slosson, 1976. Other references include Alfors et al., 1973, Briggs et al., 1975, Chassie and Goughnour, 1976, Edwards and Batson, 1980, Fleming and Taylor, 1980, Jochim et al., 1988, McCalpin, 1984, Nilsen and Turner, 1975, Pfeiffer and Bowen, 1989, Radbruch-Hall, 1979, Radbruch-Hall et al., 1976, Smith, 1958, Turner and Shuster, 1996, Varnes, 1978, Wiggins et al, 1978, and Zaruba and Vojtech, 1969.

C.2.3 Expansive Soil

Soils and soft rocks which tend to swell or shrink owing to changes in moisture content are commonly known as expansive soils. In the United States, two major groups of rocks serve as parent materials of expansive soils. Both groups are more common in the Western United States than in the Eastern United States. The first group consists of ash, glass, and rocks from volcanic eruptions. The aluminum silicate minerals in these volcanic materials often decompose to form expansive clay minerals of the smectite group, the best known of which is montmorillonite. The second group consists of sedimentary rocks containing clay minerals, examples of which are the shales of the semiarid West-Central United States.

Smectite-rich materials which serve as sources of expansive soils. Smectites are regionally abundant in geologic formations throughout the Rocky Mountains, most of the Great Plains, much of the Gulf Coastal Plain, the lower Mississippi River Valley, and the Pacific Coast. They are locally abundant in geologic formations along the Atlantic and Gulf Coastal Plains and in the Great Basin region. They are a very minor constituent of geologic formations in the rest of the United States, but they may be abundant locally in surficial deposits along both coasts and in the western and west-central parts of the Nation.

Selected sources on expansive soils include Holtz and Hart, 1978, Jones and Holtz, 1973, Krohn and Slosson, 1980, Nelson and Miller, 1992, Noe et al., 1997, Patrick and Snethen, 1976, and Tourtelot, 1974.

C.2.4 Soil Collapse

The lowering or collapse of the land surface either locally or over broad regional areas, has taken place in nearly every State. Although collapse is usually not spectacular or catastrophic, it causes several tens of millions of dollars in damages annually in the United States.

Natural subsidence results from processes including the dissolving of limestone and other soluble materials. Large areas of the United States are underlain by limestone and other soluble materials. As underground water percolates through such materials, soluble minerals dissolve, leaving cavities or caverns. Land overlying these caverns can collapse suddenly, forming sinkholes of 100 feet (30m) or more in depth and 300 feet (91m) or more in width. Other times, the land surface can settle slowly and irregularly. The landscape created by such subsidence is called karst terrain. This type of subsidence usually causes extensive damage to structures located over pits formed by dissolving the soluble minerals. Although the formation of sinkholes is a natural phenomenon, the process can be accelerated by human practices with regards to ground-water withdrawal, land development, and disposal of water.

The major locations of karst terrain and caverns in the United States are in parts of many of the Southeastern and Midwestern States. Sinkholes also are found in some of the Western and Northeastern States. Alabama, where soluble limestone and other rocks are present in nearly one-half of the state, has thousands of sinkholes that pose serious problems for highways and construction generally.

Man-induced subsidence has increased dramatically since 1940 as a result of the withdrawal of oil, gas, and water. Because undergound fluids fill intergranular spaces and support sediment grains, removal of these fluids results in a loss of grain suport, reduction of intergranular void spaces, and compaction of clays. The land surface commonly subsides wherever widespread subsurface compaction has taken place, causing damage to canals, aqueduct and pipelines, and increasing the probability of flooding in some areas. The most dramatic examples of subsidence caused by withdrawal of oil, gas, and water are along the Gulf Coast of Texas, in Arizona, and in California.

Recent research suggests that subsidence caused by withdrawal of ground water can also cause fissuring or renewal of surface movement in some areas cut by pre-existing faults. Fissuring is the formation of open cracks. Surface faulting and fissuring associated with withdrawal of ground water are believed to have either taken place or to be a potential problem in the vicinity of Las Vegas, Nevada as well as in parts of Arizona, California, Texas, and New Mexico (Holzer, 1977).

Underground mining, especially shallow coal mining, is another significant cause of subsidence. The rocks above mine workings may not have adequate support and can collapse from their own weight, either during mining or long after mining is completed. Subsidence in areas of underground mining has caused hazardous conditions in parts of Pennsylvania and other Appalachian States, Colorado, North Dakota, Wyoming, New Mexico, Washington, Iowa, and Illinois. Subsidence-related damage to surface structures is common in the area around Pittsburgh, Pennsylvania where coal has been mined extensively. Subsidence depressions and pits, forming above abandoned underground mines, are a hazard in the Sheridan, Wyoming area.

Solution mining also can cause subsidence. In solution mining, water-soluble minerals such as salt, gypsum, and potash are dissolved and pumped to the surface so that the water can be evaporated. Huge underground cavities are formed, causing surface subsidence.

Hydro-compaction, or the settling of sediments after water is added, is another significant cause of subsidence, especially in the arid to semiarid Western and Midwestern States. Areas of known compaction include San Joaquin Valley, California, Hearth Mountain-Chapman Beach and Riverton, Wyoming areas. Hysham Bench, Montana, Columbia Basin, Washington, Denver, Colorado, Washington-Hurricane area in southwest Utah and central Utah, and Missouri River Basin. Hydro-compaction takes place when dry surface or subsurface deposits are extensively wetted for the first time since their deposition as, for example, when arid land is irrigated for crop production or an irrigation canal is built on loose dry uncompacted sediments. Wetting causes a reduction in the cohesion between sediment grains, allowing the grains to move and to fill in the naturally occurring intergranular openings. The result is a lowering of the land surface from 3 to 6 feet (0.9 to 1.8m), although subsidence as much as 15 feet (4.6m) has been recorded. The effects of hydro-compaction on the land are usually uneven, causing depressions, cracks, and wavy surfaces. As a result, canals, highways, pipelines, buildings, and other structures can be seriously damaged by these hazards. Natural subsidence, man-induced subsidence and hydro-compaction can have significant impact on the change in grade for gravity-flow conveyances.

Selected references on soil collapse include Allen, 1969, Davies, 1970, Davies et al., 1976, Dunrud, 1976, Dunrud and Osterwald, 1980, Gilluly and Grant, 1949, Holzer, 1977, Jones and Larson, 1975, Lofgren, 1969, Newton, 1976, Poland and Davis, 1969, Poland and Green, 1962, Rickert et al., 1979, and U. S. Bureau of Mines, 1976.

C.2.5 Frost Heave

Frost heave is the increase in volume experienced by soils when they freeze. Water moves to the upper horizons from below; when it freezes it forms segregated ice lenses which push apart the soil around them as they grow, causing the observed volume increase. Frost heave has a number of effects upon the soil and upon structures supported by or within the soil.

During the freezing of some soils, nearly pure ice forms in segregated lenses parallel to soil isotherms (Hillel, 1980). The formation of these lenses causes frost heave, a phenomenon in which the surface of the soil is “heaved” vertically by as much as tens of inches (several tens of centimeters). The overall volume of the soil also increases greatly, and heave pressures of many atmospheres can build up (Mitchell, 1993). Frost heave often causes substantial damage to roads, foundations, lifelines, and other structures within and on top of the soil.

Three conditions are necessary for ice segregation and frost heave to occur: (1) a frost susceptible soil, (2) freezing temperature, and (3) a supply of water.

Frost heave begins when air with a sub-freezing temperature overlays a soil whose temperature is above freezing. At this point, a freezing isotherm begins moving down through the soil. The exact temperature at which the soil water begins to freeze is determined by several factors, including the amount of dissolved minerals and particle surface force effects. Regardless, ice typically begins to form before the soil reaches –0.2º C (32.4º F). Around the ice is a film of supercooled water which is gradually frozen and added to the ice mass and then replaced by water from nearby pores in the soil. Rather than freezing water in situ through the bottlenecks of the surrounding pores, which requires a great deal of energy, the ice tends to segregate, drawing water and pushing the soil away. Experiments by Beskow (1935) revealed that pore saturation had to be greater than 90% in the soil behind the freezing front for heaving to occur. This fact suggests that a great deal of water must move from lower horizons to the upper portion of the soil.

The mechanisms of frost heave suggest that certain soils are more susceptible to heaving then others. Fine-grained clays conduct water too slowly to supply a growing ice lens, while sandy soils, due to their large pore size, are poor upward conductors of water. Thus silts, which have moderate pore size, are best at providing a steady supply of water to growing lenses of ice and are most susceptible to frost heave.

Frost heave affects soils greatly. Small lateral differences in snow cover, soil texture, vegetation, and topography can lead to differences in the amount of heave experienced by regions in the soil. Differential heaving causes layers to be displaced varying distances, leading either to the formation of wavy boundaries, or, in extreme cases, to the destruction of horizon boundaries altogether. At the surface differential heaving often forms a pattern of circular bulges with depressions between them. These small bulges are better-drained than the depressions, and they thus retain their heat longer during cold spells. Frost heave then begins in the depressions first, causing lateral pressure towards the centers of the bulges. This pressure displaces more soil and pushes the bulges higher, forming hummocks, circular mounds roughly 1-2 meters (3.3-6.6 ft) in diameter and up to 5 meters (16.4 ft) high.

The final major effect of frost heave occurs during seasonal thawing. A great deal of water accumulates in the upper soil horizons when ice lenses form. During thawing, the upper portion of the soil melts first. Because the bottom layers are still frozen at this point, the melt water cannot drain. The soil becomes saturated and loses most of its strength. When soils supporting roads, fence posts, foundations, electric power and telephone poles, and other structures lose strength in this manner, the roads develop potholes while the fence posts and foundations can often become skewed. Thawing areas on slopes are also susceptible to landsliding.

Selected references include Anderson (1988), Clark (1988), Dash (1989), Hillel (1980), Mitchell (1993), and Smith (1985).

C.3 The Phenomenology of Flood Hazards

C.3.1 General Considerations

Floods have been and continue to be one of the most destructive natural hazards facing the Nation. Moreover, the probability exists that a greater flood will take place than any experienced in the past (see Figure 3).

A flood is any abnormally high streamflow that overtops the natural or artificial banks of a stream. Flooding is a natural characteristic of rivers. Flood plains are normally dry-land areas on either side of a river which act as a natural reservoir and temporary channel for flood waters when they come. If more runoff is generated than the banks of a stream channel can accommodate, the water overtops the stream banks and spreads over the flood plain causing social and economic disruption and damage to crops, lifelines and other structures. The ultimate parameter affecting damage to surface structures or crops, however, is not the quantity of water being discharged, but the elevation of the water surface above the land.

C.3.2 Riverine Flood and Scour

Taking place throughout the United States, riverine floods are caused by precipitation over large areas or by the melting of the winter's accumulation of snow or both. Riverine floods differ from flash floods or headwater flooding in their extent and duration. Whereas these floods are of relatively short duration on small streams, riverine floods take place in river systems whose tributaries may drain large geographic areas and encompass many independent river basins and states. Floods on large river systems may continue for periods ranging from a few hours to many days.

Flood flows in large river systems are influenced primarily by variations in the intensity, amount, and distribution of precipitation. The condition of the ground, amount of soil moisture, seasonal variations in vegetation, depth of snow cover, and imperviousness due to urbanization directly affects flood runoff as well.

Three characteristics of river channels, (1) channel storage, (2) changing channel capacity, and (3) timing, control the movement of riverine flood waves. As a flood moves down the river system, temporary storage in the channel reduces the flood peak. As tributaries enter the main stream, the river gets larger and larger downstream. Tributaries are not of the same size nor are they spaced uniformly; therefore, their flood peaks reach the main stream at different times. The difference of timing tends to modify peaks as a flood wave moves downstream.

Selected references include Leopold and Langbein, 1960, National Oceanic and Atmospheric Administration, 1994, U. S. Congress, 1966, Flood Protection Act of 1973, U. S. Water Resources Council, 1972, 1977, 1978, Waananen et al. 1977.

C.3.3 Headwater Flood and Scour

Headwater floods include those generated in relatively flat terrains or mountainous areas with ravines or gorges. The former can form where there is no stream. For example, abnormally heavy precipitation can fall on flat terrain at such a rate that the soil cannot absorb the water or the water cannot run off as fast as it falls.

Flash floods are local floods of great volume and short duration. A flash flood generally results from a torrential rain or “cloudburst” on a relatively small drainage area. Cloudbursts, associated with severe thunderstorms, take place mostly in the summer. Flash floods can also result from the failure of a dam or from the sudden breakup of an ice jam. Each can cause the release of a large volume of flow in a short time.

Violent thunderstorms or cloudbursts can develop in a short time. They then can produce floods on relatively small and widely dispersed streams. Discharges quickly reach a maximum and diminish almost as rapidly. Flood flows frequently contain large concentrations of sediment and debris collected as they sweep channels clean.

Flash floods can take place in almost any area of the country, but they are particularly common in the mountainous areas and desert regions of the West. Flash floods are a potential source of destruction and a threat to public safety in areas where the terrain is steep, surface runoff rates are high, streams flow in narrow canyons, and severe thunderstorms prevail.

Selected references include Davies et al, 1972, Hoxit et al., 1977, McCain et al, 1979, Ray and Kjelstrom, 1978

C.4 The Phenomenology of Windstorms

C.4.1 General Considerations

Wind hazards are divided into the categories of:

- General severe wind
- Tornado and
- Hurricane

A discussion of each can be found in (Hart, 1976). They are divided into the separate categories above for the following relative differences in severity (see Table 1, area covered and regionality).

	Severe Wind	***Tornado***	***Hurricane***
Severity	Low	High	Medium
Area covered	Medium	Low	High
Regionality	No	Yes	Yes

Table 1: Classification of Wind by the Beaufort Scale

Beaufort Number	**Wind Speed (mph)**	**Descriptor**	**Effect Observed**
0	0-1	Calm	Smoke rises vertically.
1	2-3	Light air	Smoke drifts; vanes do not move.
2	4-7	Light breeze	Leaves rustle; vanes begin to move.
3	8-12	Gentle breeze	Leaves in constant motion; light flags extended.
4	13-18	Moderate breeze	Dust, leaves raised; small branches move.
5	19-24	Fresh breeze	Small trees begin to sway.
6	25-31	Strong breeze	Large branches of trees in motion; whistling heard in wires.
7	32-38	Near gale	Whole tree in motion; resistance felt in walking against wind.
8	39-46	Gale	Twigs and small branches break; progress generally impeded.
9	47-54	Strong gale	Slight structural damage occurs; slate blown from roofs.
10	55-63	Storm	Trees broken or uprooted; structural damage begins.
11	64-73	Violent storm	Some damage all over.
12	74 and above	Hurricane	Large-scale damage, calamity.

C.4.2 General Severe Wind

Severe winds are produced by (1) thunderstorms, (2) downbursts and (3) down slope winds.

Thunderstorm and straight-line winds. Severe thunderstorms generate high winds and sometimes even tornadoes. The non-spinning (non-tornadic) types are often referred to as thunderstorm wind or straight-line wind. Although straight-line winds are normally not as intense as tornadoes, they produce far more accumulative damage than tornadoes because they occur far more frequently and affect much larger areas. This is true even in tornado-prone areas such as Kansas or Oklahoma. Straight-line winds can have speeds approaching or sometimes exceeding 100mph (44.7 m/s), causing roofs to be blown off; mobile homes, automobiles, and parked aircraft to be overturned; trees toppled; electric power and telephone lines downed; and so on.

Downbursts. A particular type of thunderstorm wind, called `a downburst, is generated by a falling mass of evaporatively cooled air frequently driven by hail and heavy rain in a parent thunderstorm. As the falling air mass impinges on the ground, it spreads out horizontally and generates strong surface winds of short duration. The situation is analogous to the flow generated by pouring water on the ground from a pail mounted on a moving truck, with the parent storm being the moving truck.

T. Fujita (1985) classified downbursts into two size groups: microbursts and macrobursts. A microburst has a small horizontal scale of the order of a few hundred meters, and has damaging winds lasting from 2 to 5 minutes. On the other hand, a macroburst covers an area on the order of 1-5 km (0.62-3.11 miles), and the damaging winds last 5 to 30 minutes. A downburst may be moving or stationary. The streamlines in a downburst can be straight or curved. A curved downburst may sometimes develop into a tornado.

Mountain downslope winds. Mountain downslope winds happen when a cold layer of air descends from the peak of a mountain or mountain chain in a manner similar to water flowing down a steep slope. Due to the acceleration caused by gravity, the wind reaching the foothill can gain speeds as high as those of hurricanes. For any air mass to be able to accelerate by gravity, the air must be a cold layer under a warm upper air generated by a cold front. This type of wind often occurs in winter when a cold front crosses a mountain (see Figure 4).

As the cold air in a mountain downslope wind descends down a mountain, not only does the wind speed increase, but the air temperature also rises due to adiabatic compression of the air caused by increasing hydrostatic pressure encountered at lower elevations. For this reason, mountain downslope winds often bring warmer temperature to low areas.

Mountain downslope winds occurring in different geographical regions are called by different names. In the Rocky Mountains areas of the United States they are called Chinook, in southern California they are called the Santa Ana wind, in the Alps of Europe they are called Foehn, and in Yugoslavia they are called Bora. Note that Foehn and Bora are not being used as generic terms for warm and cold mountain downslope winds, respectively. Many communities on the eastern slope of the Rocky Mountains are plagued by mountain downslope winds. For example, Boulder, Colorado, each year experiences more than one downslope wind of a speed exceeding 100 mph (161 km/hr), even sometimes approaching 130 mph (209 km/hr).

General Considerations

General severe wind can occur and be evaluated for locations anywhere in the country using archived NOAA wind history data. Data is available by station for extreme 1%, 5%, 10% and mean wind speeds and by day, month of the year or by year. These four data points can be computed from weather station data. It can then provide a probabilistic profile of the severe wind characteristics for any site or region.

Should the fastest-mile-of-wind or peak gusts over 30, 40 or 50 mph (48, 64 or 80 km/hr) be desired by wind engineers, these data are also available for virtually every station in the nation.

Wind velocity, whether it be noted as a sustained speed or a 3 second or 5 second gust speed, is the key measure of intensity for this hazard. Available debris such as gravel or flying broken glass from damaged structures is also a loading factor associated with severe winds. Losses sustained by above-ground structures are conditioned by shape or envelope characteristics of the structure being loaded and the load resistance capacities of the structure and its elements. These are discussed in another part of the report.

It is true that wind velocity over land surfaces is affected by the land contour and roughness factor of the land caused by trees, structures or other items which tend to slow down or channel the wind. However, these factors are accounted for by the individual weather station data that might be used.

Selected References include Abbey, 1975, ANSI/ANS-2.3, 1983, Fujita, 1985.

C.4.3 Tornado

A tornado can be thought of as a simple vortex, a rotating, spiraling fluid, like those in a draining sink or bath tub. But behind that apparent simplicity lies a complexity of fluid dynamics, air/moisture interactions, and energy transfers. The laws of physics, probability and chaos will eventually yield answers to the many puzzling questions that tornadoes present to us even to this day.

Tornadoes occur principally in the Midwest. Although Florida also can spawn a number of tornadoes, most of them of the weak variety associated with hurricanes.

Selected references include Grazulis, 1993 and Liu, 1991.

C.4.4 Hurricane—General

Hurricanes develop from a variety of tropical weather disturbances and pass through several increasingly intense phases, classified as (a) tropical depressions (with sustained winds less than 40 mph, or 64 km/hr), (b) tropical storms (with winds between 40 and 73 mph, or 64 and 117 km/hr), and finally, (c) hurricanes (with sustained winds over 73 mph, or 117 km/hr).

The typical hurricane system has a diameter of about 300 miles (483 km), although winds of hurricane force are concentrated in a much smaller area. The air system in a hurricane in the northern hemisphere spirals counterclockwise toward the storm's low pressure center (Figure 5). The air absorbs heat and moisture from the warm ocean surface and gathers speed as it moves from higher to lower pressure. This heat and moisture constitute the hurricane's energy source, which is released again near the center where the converging air flows upward in a wall of clouds (the ring of strongest wind and rain). Inside the wall, in the hurricane eye, winds are much weaker, heavy rains cease, and the sky may even be clear.

Table 2: Construct of a Hurricane Damage system

Hurricane	Storm Center
Hazard	• Wind • Rain • Low central atmospheric pressure
Exacerbation	• Local Tides • Local coastal configuration
Results	• Wind damage from hurricane and spawned tornadoes • Storm Surge • Riverine flooding and scour • Headwater flooding and scour
Losses	• Structures & contents, including lifeline structures and equipment, such as roads, bridges, and roadway culverts • Lives/injuries • Communications • Beach erosion • Fire • Shipping & fishing • Soil fertility from saline intrusion • Land subsidence • Water supply contamination • Vegetation • Crops • Livestock

The forward movement of the hurricane system is relatively slow, usually around 12-15 mph (19-24 km/hr) in the lower latitudes. At latitudes above North Carolina the forward movement picks up to about 30 mph (40 km/hr). In general, although it is difficult to predict, the system moves with the speed and in the direction of the steering wind current, usually with some drift to the north. A west northwest drift will eventually carry most storms to higher latitudes where they tend to recurve from traveling left or westward to the right or eastward as they enter the mid-latitude westerlies. Movement of a hurricane over land or into regions of cooler air and water surface temperatures reduces the primary source of energy, and the intensity of the storm decreases or attenuates.

Table 2 represents the hurricane hazard damage system.

No segment of the Gulf and Atlantic coasts of the U.S. is without some vulnerability to hurricanes, but some areas have a history of more frequent hurricane occurrence than others. Parts of Texas, Louisiana, Mississippi, Alabama, Florida, and (to a lesser extent) South and North Carolina have been especially susceptible.

Hurricanes usually occur during the months of July, August, September, and October with the so-called season beginning in June and ending in November.

Selected references include Anthes, 1992, Baker and Miller, 1990, Burton and Kates, 1964, Coch, 1994, Diaz and Pulwartz, 1997, Emmanuel, 1987, Goldenberg and Shapiro, 1993, Gray et al., 1996, Hastenrath, 1990, Herbert et al., 1993, Herbert and Taylor, 1979a, 1979b,, Riebsame et al., Sheets, 1994, White, 1994, Wilson, 1994.

C.4.5 Hurricane-Tornado

The impact of hurricane-generated tornadoes will receive only cursory attention here for two reasons: First, the probability of this event affecting any given structure is quite small; second, the damage potential from such events is generally less than that of the sustained winds and gusts of a mature hurricane.

Hurricane tornadoes develop in the spiral rainbands, mostly in the right-front quadrant outside the areas of sustained hurricane or gale-force winds. Figure 6 shows the centroid and distribution of hurricane tornadoes. Although some hurricanes produce families of tornadoes, the individual event is a small, rope-type vortex similar to a waterspout. It has a short path length and maximum wind speeds are usually less than 120mph, (93 km/hr) (F1). Figure 7 shows the distribution of tornadoes that have accompanied past hurricanes.

General damage algorithms from hurricane winds include the sporadic inclusion of tornadoes with the total winds generated being the operative parameter for damage estimation purposes.

Selected references include Golden, 1970, Gray and Novlan, 1974, Person and Sadowski, 1965,

C.4.6 Hurricane-Cyclone Wind

Cyclone wind is the element most commonly associated with hurricanes. Highest wind speeds occur in a narrow ring usually extending 10-30 miles (16-48 km) from the center of the hurricane (see Figure 5). The highest measured gust wind speed was 197 mph (317 km/hr) in the Hurricane Inez, but gusts of 220 mph (354 km/hr) have been estimated from damages and barometric pressure records. In a major hurricane, gusts between 73 and 120 mph (117 and 193 km/hr) may extend 100 miles (161 km) from the center of the eye.

Minor damages begin with sustained winds of approximately 50 mph (80 km/hr). Moderate damages, such as broken windows and displaced shingles begin with winds of around 60 mph (97 km/hr), and structural destruction begins when wind speeds reach about 100 mph, or 161 km/hr (see Tables 1 and 2).

Table 3: Saffir/Simpson Hurricane Scale Ranges

Hurricane Category	Central Pressure: Mm of mercury at 0 degrees C (32 degrees F)	Central Pressure: Sea level pressure (inches)	Sustained Winds	Approximate Storm Surge Height (ft.)	General Damage Expectancy
Tropical Depression	≤ 1008	≤ 29.77	< 40 mph (< 64 km/hr)	≤ 2 ft (≤ 0.61m)	Virtually none
Tropical Storm	979-1007	28.91-29.74	40-73 mph (64-117km/hr)	2-3 ft (0.61-0.91m)	Some
1	980-992	28.94-29.30	74-95 mph (118-153 km/hr)	4-5 ft (1.22-1.52m)	Small
2	965-979	28.50-28.91	96-110 mph (154-177 km/hr)	6-8 ft (1.83-2.44 m)	Moderate
3	945-964	27.91-28.47	111-130 mph (178-209 km/hr)	9-12 ft (2.74-3.66m)	Extensive
4	920-944	27.17-27.88	131-155 mph (210-249 km/hr)	13-18 ft (2.96-5.49m)	Extreme
5	< 920	< 27.17	> 155 mph (>250 km/hr)	>18ft (> 5.49m)	Catastrophic

Saffir and Simpson have devised a five category scale of hurricane intensity which is being used increasingly to describe or rate the intensity of hurricanes. It gives a general indication of both wind speed and expected storm surge height (see Table 3 and compare it to Table 1).

The likelihood of occurrence of storms having varying strength as expressed on the Saffir-Simpson scale can be treated in several ways. First the landfall probabilities in various mainland gulf and Atlantic coastal states can be expressed as indicated in Chapter 3 volume 1. A smoothed strike frequency can be constructed from this data for all tropical storms (see Chapter 3 volume I).

Selected references include Batts et al., 1980, Brinkmann, 1975, Cobb, 1991, Dunn and Miller, 1960, Emanuel, 1987, Gray, 1994, Ludlam, 1963, Nalivkin, 1982, Neumann et al., 1981, Russell, 1971, Sheets, 1990, U. S. Department of Commerce, 1993.

C.4.7 Hurricane-Storm Surge and Scour

About 90% of the deaths experienced in the past near the coast resulting from hurricanes are caused not by wind, but by storm surge. Storm surge is the rise of water above sea level at the time of storm onset. The height of storm surge along the open coast depends on a number of factors which include: (1) wind speed and associated barometric pressure, (2) depth of water or shoaling factor, (3) storm trajectory, and (4) speed of the storm (Figure 8). Coastal configuration in the form of estuaries or bays can cause a funneling or amplification effect. Coincidence with high astronomical tide will also increase surge height. Although the maximum surge usually affects only a relatively short length of coastline, combined storm surge and wave action may have damaging effects over 100 miles (161 km) away in either direction of a major storm center.

Wind-driven waves on top of the storm surge pose a number of added problems. First of all, the wave run-up can flood areas not reached by the surge itself. Second, the battering action of waves can transmit tremendous force inland through soil pore water pressure in the saturated soils to fairly distant structures. Third, the scouring power of waves is considerable.

The duration of storm surge is usually relatively short, being dependent upon the elevation of the tide which rises and falls twice daily in most coastal places and the speed of a storm's onset. However, maximum tide elevations can be identical on consecutive days. The high velocities of hurricane winds often produce wave heights higher than the maximum level of the prevailing high tide.

The SLOSH computer model developed for FEMA computes the run-up on shore of storm surge waters. These are included and addressed by all FEMA 100 year and 500 year flood maps in the coastal areas of the U.S. Riverine and headwater flood coverage is commingled on these maps.

Storm-surge flooding is water that is pushed up onto otherwise dry land by onshore winds. Friction between the water and the moving air creates drag that, depending upon the distance of water (fetch) and the velocity of the wind, can pile water up to depths greater than 20 feet (6.1m) from the shoreline inland. The storm surge is unquestionably the most dangerous part of a hurricane as pounding waves create very hazardous flood currents. Worst-case scenarios occur when the storm surge occurs concurrently with high tide. Stream flooding is much worse inland during the storm surge because of backwater effects.

A conceptual idea of how a storm surge is that the water is pushed by the winds on the right side of the storm on to land. Winds on the left side of the storm actually push waters out of estuaries because of the seaward flow of the wind on that side.

Selected references include Department of the Army, Corps of Engineers, 1973, Jelesnianski and Taylor, 1973, Jelesnianski, 1974, Mitchell, 1893.

C.4.8 Hurricane-Headwater Flood and Scour

Heavy rainfall often accompanies hurricanes and can result in severe local inland flooding, here called headwater flooding. The amount of rainfall depends on many factors including forward speed of the storm and topography. The power of headwater flooding can be awesome in its ability to destroy not only constructed works, but also the countryside, flora and fauna.

Selected references include Conrad, 1942, Haurwitz, 1935, Ooyama, 1969, Riehl, 1979, Simpson, 1951.

C.4.9 Hurricane-Riverine Flood and Scour

Since riverine flooding accompanies all hurricanes to some degree it is also addressed here. Wind damage is usually minimal beyond about 100 miles (161 km) from a coastline locating the onset of a hurricane storm. Riverine flooding is not usually described as being experienced within this so-called first tier region. Rather, with exceptions, it is the winds, tornadoes, storm surges and headwater floods which are described as causing most of the damage in the first tier region.

Usually, riverine floods from hurricanes are described as affecting primarily areas inland from the 100 mile (161 km), hypothetical limit of wind and other subordinate hazard damages. They are still generated by locally generated heavy rains as the hurricane, cyclonic air mass passes over land. However, in the absence of heavy winds tornadoes and storm surge the headwater flood generated from heavy local rains can cause river level elevations outside of the heavy rainfall areas downstream to generate riverine flooding as well as headwater floods within those areas.

Selected references include Bailey et al. 1975, Bohman and Scott, 1980.

C.5 The Phenomenology of Earthquakes

C.5.1 General Considerations

An earthquake causes sudden trembling of the Earth as the result of abrupt release of slowly accumulating strain along a fault. The theory of plate tectonics can explain the majority of earthquakes. In this theory, re-introduced in 1967, the “solid” Earth is broken into several major plates. These 50- to 60-mile-thick (80- to 97- km) rigid plates or segments of the Earth’s crust and upper mantle move or float slowly and continuously over the interior of the Earth, meeting in some areas and separating in others. Speeds of relative motion between adjacent plates range from a fraction of an inch to about 5 inches (12.5 cm) per year. These intraplate earthquakes constitute perhaps 90% of the world’s earthquakes; another 10% of the world’s earthquakes are intraplate.

Hazards associated with earthquakes include the phenomena of surface faulting and attendant ground shaking as well as earthquake-induced landslides, liquefaction, lurching, tsunamis, seiches, and fire following.

Communities throughout the Nation face the possibility of loss from the several thousand earthquakes that happen each year. The greatest threat is from moderate earthquakes (magnitudes of 6-7) and large earthquakes (magnitudes of 7-8) because they happen more frequently than a great earthquake (magnitudes of 8 and above). For example, one moderate earthquake takes place on the average about once every 3 years in California, but a great one happens only about once every 180 years. Earthquakes happen most frequently in Alaska and least frequently in the Eastern United States (see Figures 9 and 10). A large set of earthquakes, such as the 1811-12 New Madrid, Missouri, earthquake series happens about once every 700 years in that area. Locations of moderate and large earthquakes in the east include the St. Lawrence River region from 1650 to 1928, in the vicinity of Boston in 1755, in the central Mississippi Valley in 1811-12, and near Charleston, South Carolina, in 1886.

C.5.2 Local Earthquake—Fault Rupture

The differential movement of the two sides of a fracture at the Earth's surface is of three general types: strike-slip, normal, and reverse (see Figure 11). Combinations of the strike-slip type and the other two types of faulting can be found. Although displacements of these kinds can result from landslides and other shallow, earth failure processes, surface faulting, as the term is used here, applies to differential movements caused by deep-seated tectonic or volcanic forces in the Earth, the slow movement of sedimentary deposits toward the Gulf of Mexico, and faulting associated with salt domes.

Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, the damage to structures located in the fault zone can be very high, especially where the land use is intensive. A variety of structures have been damaged by surface faulting, including houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, and water, gas, and sewer lines. Damage to these types of structures has ranged from minor to very severe.

The displacements, lengths, and widths of surface fault ruptures show a wide range. Fault displacements in the United States have ranged from a fraction of an inch (2.54 cm) to more than 20 feet (6.1 m) of differential movement. As expected, the severity of potential damage increases as the size of the displacement increases. The lengths of the surface fault ruptures on land have ranged from less than 1 mile (1.61 km) to more than 200 miles (322 km). Most fault displacement is confined to a narrow zone ranging from 6 to 1,000 feet in width, but separate subsidiary fault ruptures may occur 2 to 3 miles (3.2 to 4.8 km) from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone.

Avoidance, system redundancy, and engineering design including flexibility to accommodate the differential displacements are the primary actions that will reduce losses from surface faulting. Avoidance requires accurate location of the fault and an assessment of its history of activity through a detailed geologic or earthquake hypocenter examination. Structures, such as pipelines, dams, bridges, and aqueducts, sometimes cannot be built without crossing active faults. Some of these structures have been designed and constructed to accommodate some fault displacements in an earthquake.

Areas in the United States where young surface faults are known to exist are mapped by the U.S.G.S. (See Chapter 3, volume 1). This map shows faults in two general categories-those that have had displacement within the last 10,000 years (Holocene period) and those that have had displacement within the last 2 million years (Quaternary period). Faults can lie dormant for many thousands of years between periods of vigorous activity, and, therefore, their behavior over a substantial part of their recent history must be considered probabilistically. Those with very long return intervals may still contribute to the overall risk to a water system—at least in defining extreme risks.

The national atlas website (Chapter 3, volume 1) locates these faults more precisely in pictorial form while the table of USGS, National Seismic Hazard Mapping Project-Fault parameters precisely locates the active faults and their widths. State Geologists have even more detailed information on fault location and age for each of their states, should the USGS data be deemed to be incomplete. The State of California, for instance, has for three decades undertaken extensive mapping of active fault traces.

Selected references include Blair and Spangle, 1979, Bonilla, 1979, Cluff and Bolt, 1969, Hart, 1977, Howard et al., 1978, Kockelman, 1980, Russ, 1979, Verbeek, 1979.

C.5.3 Earthquake—Shaking

Ground shaking is caused by body and surface traveling seismic waves. As a generalization, the severity of ground shaking increases as the magnitude or earthquake size increases and decreases as distance from the causative fault increases. Surface and buried structures are more easily damaged from horizontal motions than from vertical motions.

Body waves mainly cause high-frequency vibrations (less than two seconds per cycle), surface waves only low frequency vibrations. Body and surface waves cause the ground, and consequently a structure to vibrate in a complex manner. The objective of most earthquake-resistant design for surface structures is to construct a structure so that it can withstand the ground shaking.

In land-use zoning and earthquake-resistant design, knowledge of the amplitude, frequency composition, and the time duration of ground shaking is desirable. These quantities can be determined from empirical data and correlating them with the magnitude and the distribution of Modified Mercalli Intensity of the earthquake, distance of the structure from the causative fault, and the physical properties of the soil and rock underlying the structure. The subjective Modified Mercalli Intensity Scale indicates the intensity of ground shaking on man, structures and the surface of the Earth. It can be correlated with physical shaking properties.

The size of the geographic area affected by ground shaking depends on the magnitude of the earthquake and the rate at which the amplitudes of seismic waves decrease as distance from the causative fault increases. Comparison of the areas affected by the same Modified Mercalli intensity of ground shaking in the 1906 San Francisco, California, the 1974 Northridge, California, the 1811-12 New Madrid, Missouri, and the 1886 Charleston, South Carolina, earthquakes shows that a given intensity of ground shaking extends over a much larger area in the Eastern United States than it does in the west for comparable magnitude events. Ground shaking affects a larger area east of about the 104 degree longitude line because amplitudes of seismic waves decrease more slowly than those west of the 104 degree longitude line, as distance from the causative fault increases.

Considerable efforts have been undertaken by government, academicians, and consultants to evaluate earthquake hazards from strong ground motions. Particular reference is made to efforts by the USGS to develop probabilistic strong ground motion maps. These maps define strong ground shaking at various return intervals (e.g., 50 year life with a 10%, 5% and 2% chance of occurrence) for the entire United States (see Chapter 3, volume 1). These efforts may be called probabilistic seismic (site) hazard evaluations (PSHA's). As noted throughout this document, evaluating water systems risks requires the use of individual scenarios, since they are not located at a single site. As a consequence, with rare exceptions, the results of PSHA's are not useful in the actual evaluation of water system risks—unless water utility systems are small in spatial extent. However, the models developed by geoscientists and engineers in constructing probabilistic seismic hazard maps can be desegregated and then recombined to produce bases for earthquake hazard evaluations.

Of special interest in the USGS source is a catalog of previous historic earthquakes. These can provide a first basis for constructing specific scenarios. More detailed investigations of existing fault systems can provide as needed greater detail on specific earthquake scenarios—treated first as repetitions of past history. Likewise, various other entities (such as Tri-Net) have developed deterministic scenarios that may be useful in intermediate-level operations evaluations for water utility systems.

Selected references include Abrahamson and Silva, 1997, Algermissen and Perkins, 1976, Bolt, 1993, Borcherdt, 1975, Federal Emergency Management Agency, 1981, Frankel et al., 1996, Hays, 1980, Hwang and Huo, 1997, Nuttli, 1973, Somerville, 1997, J. H. Wiggins, 1979.

C.5.4 Earthquake—Landslide

Because certain types of ground failures are frequently associated with earthquakes as well as other causes such as gravity, moisture changes, etc. they will be discussed in this section (as well as in C.2) for continuity.

Several types of landslides take place in conjunction with earthquakes. The most abundant types of earthquake-induced landslides are rock falls and slides of rock fragments that form on steep slopes. Shallow debris slides forming on steep slopes and soil and rock slumps and block slides forming on moderate to steep slopes also take place, but they are less frequent. Reactivation of dormant slumps or block slides by earthquakes is rare and is most likely preceded by heavy or continuous rains.

Large earthquake-induced rock avalanches, soil avalanches, and underwater landslides can and do occur. They can be very destructive. Rock avalanches originate on over-steepened slopes in weak rocks. The size of the area affected by earthquake-induced slope failures depends on the magnitude of the earthquake, its focal depth, the topography and geologic conditions near the causative fault, and the amplitude, frequency composition, prior rains or other sources of wetting and duration of ground shaking. In past earthquakes, landslides have been abundant in some areas having intensities of ground shaking as low as VI on the Modified Mercalli Intensity Scale or about 6% of gravity as the associated peak acceleration. In this case the earth material was already in a state of incipient failure.

Selected references include Brown and Kockelman, 1983, Keefer et al., 1978, Nilsen et

al., 1979, Seed, 1970, Youd and Hoose, 1978.

C.5.5 Earthquake—Lurching/Lateral Spreads

Lurching includes lateral spread, flow failures and loss of bearing strength during an earthquake. It is sometimes hard to distinguish landslide from lurching or liquefaction since land failure is the common result of each. Lateral spreads involve the movement of large blocks of soil as a result of liquefaction in a subsurface layer. Movement takes place in response to the ground shaking generated by an earthquake. Lateral spreads generally develop on gentle slopes, most commonly on those between 0.3 and 3 degrees. Horizontal movements of lateral spreads commonly are as much as 10 to 15 feet (3.0 to 4.6 m), but, where slopes are particularly favorable and the duration of ground shaking is long, lateral movement may be as much as 100 to 150 feet (30 to 46 m). Lateral spreads usually break up internally, forming numerous fissures and scarps in the surficial earth materials.

Lateral spreads are particularly destructive to pipelines.

Flow failures, consisting of liquefied soil or blocks of intact material riding on a layer of liquefied soil, are the most catastrophic type of ground failure caused by lurching. These failures commonly move several tens of feet and, if geometric conditions permit, several tens of miles. Flows travel at velocities as great as many tens of miles per hour. Flow failures usually form in loose saturated sands or silts on slopes greater than 3 degrees.

Flow failures can originate either underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas.

When the soil supporting a structure loses strength due largely to the presence of water from frequent precipitation or seaside infiltration, large deformations can occur within the soil, allowing the structure to settle and tip.

Actions for reducing damage due to loss of bearing strength include: (1) site selection to avoid the hazard, (2) stabilization of liquefiable layers to prevent loss of strength, and (3) use of deep foundations (such as piles) to transfer loads to stable layers underlying potentially liquefiable ones.

C.5.6 Earthquake—Liquefaction

Liquefaction is a physical process that takes place during some earthquakes that may lead to ground failure. As the name suggests, water must saturate the interstices (be below the water table) of the grains making up the soil. As a consequence of liquefaction, clay-free soil deposits (primarily fine sands and silts) temporarily lose strength and behave as viscous fluids rather than as solids. Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. Disruptions to the soil generated by these collapses cause the transfer of the ground shaking load from grain-to-grain contacts in the soil layer to the interstitial pore water. This transfer of load increases pressure in the pore water, either causing drainage to occur or, if drainage is restricted, a sudden buildup of pore-water pressure. When the pore-water pressure rises to about the pressure caused by the weight of the column of soil, the granular soil layer behaves like the fluid water rather than like the solid grains for a short period. In this condition, soil deformations can occur easily.

Liquefaction can be associated with landslide and lurching as the earlier discussion of these hazards suggests. However, in this section it is referred primarily to areas with no slope. It is restricted to certain geologic and hydrologic environments, mainly areas where sands and silts were deposited in the last 10,000 years and where ground water table is within 30 feet (9.1m) of the surface. Generally, the younger and looser the sediment and the higher the water table, the more susceptible a level soil is to liquefaction.

Actions for reducing losses from liquefaction include: (1) zoning to limit construction in susceptible areas, (2) stabilization to prevent liquefaction and ground failure, and (3) construction of displacement-resistant foundations. Engineering techniques for stabilizing sites against liquefaction include compaction, grouting, or drainage of susceptible soils. These techniques are generally expensive and, therefore, are not economically feasible unless critically important water supply and other lifeline facilities are being built. Construction of displacement-resistant foundations is presently beyond the state-of-the-art for ground-failure displacements greater than about one foot (0.3 m).

Selected references include California Division of Mines and Geology, 1992, Leighton and Associates, 1993, Youd, 1992, Youd and Hoose, 1978.

C.5.7 Earthquake—Tsunami

Tsunamis are water waves that are caused by the sudden vertical movement of a large area of the sea floor during an undersea earthquake. (Note that an earthquake that occurs on land can trigger submarine slips, which in turn can create tsunamis.) The earthquake may be tectonic or volcanic in origin. Tsunamis are often called tidal waves, but this term is a misnomer. Unlike regular ocean tides, tsunamis are not caused by the tidal action of the Moon and Sun.

The height of a tsunami in the deep ocean is typically about one foot (30 cm), but the distance between wave crests can be very long, more than 60 miles (96.5 km). The speed at which the tsunami travels decreases as water depth decreases. In the mid-Pacific, where the water depths reach about 3 miles (4.8 km), tsunami speeds can be more than 400 miles per hour (644 km/hr). As tsunamis reach shallow water around islands or a shallow continental shelf, the height of the waves increases may times, sometimes reaching as much as 80 feet (24m). (During the eruption of Krakatoa in Indonesia waves of about 200 feet (or 61m) were observed.) The great distance between wave crests prevents tsunamis from dissipating energy like a breaking surf; instead, tsunamis cause water levels to recede and rise rapidly along coast lines.

Tsunamis and earthquake ground shaking differ in their destructive characteristics. Ground shaking causes destruction mainly in the vicinity of the causative fault, but tsunamis cause destruction both locally and at very distant locations from the area of tsunami generation since they can travel thousands of miles with very little amplitude attenuation.

A current theory under development is that during an earthquake some of the largest localized tsunamis are caused by underwater landslides instead of by the motion of the seafloor. From an emergency standpoint, the implication is “If you see the sea receding, get out and stay out!” This viewpoint saved many lives in the village Biai Martele in Vanuatu, affected by a tsunamis in December, 1999 (See Douglas Smith, 200; Tappin et al., 2002; Grilli and Watts, 2001)

Destruction to structures and other facilities is a consequence of the time between successive wave crests, the wave heights at the shoreline and inland locations, and the wave and current velocities. The effects of tsunamis include structural failure, scouring, erosion, flooding, and movement of stone and debris.

Selected references include Houston, 1980, Houston et al., 1977, Wiegel, 1970.

C.5.8 Earthquake—Seiche

A seiche is a natural standing wave in the water of a lake or bay. It can be caused by seismic disturbances, among other causes, and continues after the seismic shaking has stopped. Every enclosed body of water has a number of natural resonances. If you sit in a bathtub part full of water and rock back and forth you'll find that at the right period (about a second) you can easily get the waves to grow until they overflow the bath. The reasonant oscillation of the water is a seiche. Seiches are often generated in swimming pools by small oscillations from earthquakes – the oscillations happen to be at the right frequency for the swimming pools to "catch" them.

Seiching is the formation of standing waves in a water body, due to wave formation and subsequent reflections from the ends. These waves may be incited by earthquake motions (similar to the motions caused by shaking a glass of water), impulsive winds over the surface, or due to tsunami wave motions entering a basin. The various modes of seiching correspond to the natural frequency of the water body.

A rectangular basin (of infinite width)with given length and depth is modeled as seiching in accordance with mode that is specified. The period of seiching (T) is determined by finding the correct length wave that will fit in the basin for the given water depth (based on linear water wave theory). For shallow water theory, the seiching period is given by twice the basin length (l) divided by the modal number (n) and the speed of a shallow water wave, which depends on the water depth h:

$$T = 2l/(n*(gh)^{0.5})$$

There are an infinite number of seiching modes possible, from the lowest (mode 1) to infinity. The period of oscillation decreases with mode number. Realistically, the lower modes probably occur in nature, as frictional damping reduces the amplitudes of the higher modes (higher frequency).

San Francisco Bay is used as an example. If the length is 2 miles (3.21km) and the depth 50 feet (15.2m), then the period of the first mode is 264 seconds. The 30th mode is about 9 seconds. Nearby earthquakes are not expected to stimulate these modes. Any higher modes within the frequency range would experience damping. Only large distant earthquakes with clearly defined surface waves may excite San Francisco Bay. These might originate on the eastside of the Sierra Madre range. However, the only known earthquake that occurred at distance, the 1964 Great Alaskan earthquake, did not cause visible seiche.

Selected reference: Chapters 4 and 5 of Dean And Dalrymple.

C.5.9 Earthquake—Fire Following

Earthquake shaking or failures of structures by other means (landslide, lurching, etc.) can cause electrical shorts, gas pipe breakage and other fire sources to generate fires and even result in conflagrations. While many aspects of fire and earthquakes have been investigated in recent years, one aspect that has been little treated has been the subject of fire spread in an urban region following an earthquake. That fire following earthquake has been little researched or considered in the United States is particularly surprising when one realizes that the conflagration in San Francisco, following the 1906 earthquake, was the single largest urban fire and the single largest earthquake loss in American history.

The earthquake of April 18, 1906, of earthquake moment magnitude 7.8 was the result of the San Andreas fault rupturing along more than 200 miles (320km) of its length. The shaking damage in the City of San Francisco was considerable, especially in the soft filled-in ground along the bay, on which much of the central business district was located, where permanent ground displacements of several feet were noted in numerous locations. Especially severely affected by these large ground displacements were the underground water pipes. The hundreds of breaks in these pipes resulted in loss of virtually all water in this densely built-up area, so that the fire department was helpless to stop the dozens of fires which ignited almost immediately following the earthquake.

The post-earthquake fire problem is complex and involves many diverse elements. The recent California earthquakes have pointed out some of these elements:

1. Fire departments functioned well but were inundated with numerous demands involving not only fire but structural damage, search and rescue, hazardous material incidents and medical aid,
2. Communications were seen to be extremely vital, but highly vulnerable, especially with regard to reporting initial fires to the fire departments,
3. Due to delays in reporting, fires rapidly grew larger, escalating demands on fire service resources.

Thus, the fire following earthquake hazard is not so much a problem of single ignitions scattered around and within a densely populated region as it is the source of possible conflagration. The elements are ripe in older areas where buildings are closely spaced and streets are narrow. The traffic jams alone could prevent fire department teams from reaching an individual fire which, left unattended, could erupt into a conflagration source. The resulting conflagration would be very difficult for all of the fire fighting forces available to contain such a fire.

Selected references include Scawthorn, 1987, Wiggins, 1988, Scawthorn, 2002.